

**TECHNIQUE FOR INTERCHANGING WAVELENGTHS**  
**IN A MULTI-WAVELENGTH SYSTEM**

**CROSS-REFERENCE TO RELATED APPLICATIONS**

5        This patent application is related to U.S. Patent  
Application No. \_\_\_\_\_ (Attorney Docket No. 57983-  
000012, Client Reference No. 12867RO), filed concurrently  
with this patent application, and which is hereby  
incorporated by reference herein in its entirety.

10       This patent application is also related to U.S.  
Patent Application No. \_\_\_\_\_ (Attorney Docket No.  
57983-000015, Client Reference No. 12922RO), filed  
concurrently with this patent application, and which is  
hereby incorporated by reference herein in its entirety.

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**FIELD OF THE INVENTION**

20       The present invention relates generally to  
wavelength interchangers and, more particularly, to a  
technique for interchanging wavelengths in a multi-  
wavelength system.

**BACKGROUND OF THE INVENTION**

25       To fully exploit the bandwidth promised by fiber-  
optic transmissions, it is necessary to build all-optical  
networks where optical signals are not converted into an  
electrical form, except at ingress or egress nodes. In  
circuit-switched wavelength division multiplexing  
networks, all-optical routing is provided by all-optical  
cross-connects capable of switching individual wavelength  
30 channels. Circuit-switched wavelength division  
multiplexed networks share some of the characteristics of  
traditional circuit-switched networks. However, major

To address the same problem, another approach is to try and design fully-convertible cross-connects using a minimum number of all-optical converters (see N. Antoniadou, S. Yoo, K. Bala, G. Ellinas, and T. Stern, "An architecture for a wavelength-interchanging cross-connect utilizing parametric wavelength-converters", IEEE Journal of Lightwave Technology, vol. 17, pages 1113-1125, July 1999). Before the development of wave-mixing wavelength converters, this approach has inevitably lead to solutions that assigned a dedicated full-range

With these previous approaches, strictly non-blocking fully-convertible nodes require a number of converters equal to the total number of wavelength channels (in all the fibers). A common characteristic of these first designs is to convert channels through a single wavelength conversion operation, usually carried out at the inputs or at the outputs of a space switch. For this class of solutions, the problem lies in high converter costs. Indeed, for a cross-connect with  $F$  fibers and  $W$  frequencies per fiber, these solutions require as many as  $FW$  dedicated all-optical converters.

25 Unlike previous techniques based on single-stage  
wavelength conversion, this approach converts individual  
wavelength channels by decomposing these conversions into  
several elementary wavelength conversions operations (see  
N. Antoniadou et al. referenced above). Also, in this  
30 design, the resulting cross-connect architecture is  
rearrangeably non-blocking and only uses a number of  
wave-mixing converters equal to half the total number of  
wavelength channels (see N. Antoniadou et al. referenced

above). In other words, for a cross-connect with  $F$  fibers and  $W$  frequencies per fiber, this solution only requires a total of  $FW/2$  wave-mixing converters (see N. Antoniadou et al. referenced above), instead of  $FW$  converters, as would be obtained with other approaches (see B. Ramamurthy et al. referenced above).

In spite of its merits, this design is only rearrangeably non-blocking. Therefore, when it is used, ongoing connections may have to be rearranged to switch new requests. However, high traffic volumes make it difficult to reroute existing lightpaths, without incurring severe QoS degradation. It is possible to build strictly non-blocking cross-connects by combining this solution with the technique of vertical replication (see A. Pattavina, Switching Theory, Wiley, 1998). Yet, when doing so, more converters are required than by other designs based on dedicated wavelength converters.

Another problem of this transformation solution is that it is not adapted to provide a gradual deployment of wavelength conversion (see N. Antoniadou et al. and R. Thompson et al. referenced above). Indeed, current semiconductor technology makes it possible to build large wavelength-selective cross-connects at low costs. However, all-optical wavelength converters are in their early development stages, and are still produced at high costs. In a metropolitan network environment, service providers would prefer to start with a simple wavelength-selective cross-connect to minimize initial costs. They would then have the flexibility to upgrade the all-optical wavelength conversion capabilities when special needs appear.

In view of the foregoing, it would be desirable to provide a technique for interchanging wavelengths in a multi-wavelength system in an efficient and cost effective manner which overcomes the above-described  
5 inadequacies and shortcomings.

#### SUMMARY OF THE INVENTION

According to the present invention, a technique for interchanging wavelengths in a multi-wavelength system  
10 having W wavelength channels is provided. In one embodiment, the technique is realized by selectively directing a pair of adjacent frequency channels corresponding to a respective pair of adjacent wavelength channels based upon a routing algorithm. The frequencies  
15 of the selectively directed pair of adjacent frequency channels are then interchanged. The interchanged frequencies of the selectively directed pair of adjacent frequency channels are then selectively shifted based upon a binary representation of each interchanged  
20 frequency.

In accordance with other aspects of the present invention, the pair of adjacent frequency channels are beneficially selectively directed by selectively  
25 switching the pair of adjacent frequency channels to one of two output pairs. In accordance with further aspects of the present invention, the frequencies of the selectively directed pair of adjacent frequency channels are beneficially interchanged by routing the selectively  
30 directed pair of adjacent frequency channels based upon a binary representation of the frequency of each of the selectively directed pair of adjacent frequency channels.

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The frequencies of the selectively directed pair of adjacent frequency channels are then further beneficially interchanged by shifting the frequency of a first of the selectively directed pair of adjacent frequency channels  
5 by an amount defined by  $+\Delta f$  and shifting the frequency of a second of the selectively directed pair of adjacent frequency channels by an amount defined by  $-\Delta f$ , wherein  $\Delta f$  is the frequency spacing between the pair of adjacent frequency channels.

10 In accordance with still further aspects of the present invention, the interchanged frequencies of the selectively directed pair of adjacent frequency channels are beneficially selectively shifted by routing the selectively directed pair of adjacent frequency channels  
15 based upon the binary representation of each interchanged frequency. The interchanged frequencies of the selectively directed pair of adjacent frequency channels are then further beneficially selectively shifted by shifting the frequency of at least one of the selectively  
20 directed pair of adjacent frequency channels by an amount defined by  $\pm(2^h-1)\Delta f$ , wherein  $h=0,\dots,w-1$ ,  $w=\log_2 W$ , and  $\Delta f$  is the frequency spacing between the pair of adjacent frequency channels. Alternatively, the interchanged frequencies of the selectively directed pair of adjacent  
25 frequency channels are then further beneficially selectively shifted by shifting the frequency of at least one of the selectively directed pair of adjacent frequency channels by an amount defined by  $-2^h\Delta f$ , increasing the shifted frequency of the at least one of  
30 the selectively directed pair of adjacent frequency channels, and then shifting the increased shifted frequency of the at least one of the selectively directed

pair of adjacent frequency channels by an amount defined  
by  $+\Delta f$ , wherein  $h=0,\dots,w-1$ ,  $w=\log_2 W$ , and  $\Delta f$  is the  
frequency spacing between the pair of adjacent frequency  
channels. Alternatively still, the interchanged  
5 frequencies of the selectively directed pair of adjacent  
frequency channels are then further beneficially  
selectively shifted by shifting the frequency of at least  
one of the selectively directed pair of adjacent  
frequency channels by an amount defined by  $-\Delta f$ ,  
10 decreasing the shifted frequency of the at least one of  
the selectively directed pair of adjacent frequency  
channels, and then shifting the decreased shifted  
frequency of the at least one of the selectively directed  
pair of adjacent frequency channels by an amount defined  
15 by  $+2^h \Delta f$ , wherein  $h=0,\dots,w-1$ ,  $w=\log_2 W$ , and  $\Delta f$  is the  
frequency spacing between the pair of adjacent frequency  
channels.

The present invention will now be described in more  
detail with reference to exemplary embodiments thereof as  
20 shown in the appended drawings. While the present  
invention is described below with reference to preferred  
embodiments, it should be understood that the present  
invention is not limited thereto. Those of ordinary skill  
in the art having access to the teachings herein will  
25 recognize additional implementations, modifications, and  
embodiments, as well as other fields of use, which are  
within the scope of the present invention as disclosed  
and claimed herein, and with respect to which the present  
invention could be of significant utility.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

In order to facilitate a fuller understanding of the present invention, reference is now made to the appended drawings. These drawings should not be construed as limiting the present invention, but are intended to be  
5 exemplary only.

Figure 1 shows an exemplary prior art optical-gating wavelength converter.

Figure 2 shows a prior art wave-mixing wavelength converter based on difference-frequency generation.

10 Figure 3 shows a prior art frequency shifter wherein frequency translation is implemented with two cascaded difference-frequency generation devices.

Figure 4 shows a prior art wavelength-interchanging cross-connect based on output-dedicated full-range  
15 wavelength converters.

Figure 5 shows a prior art wavelength-interchanging cross-connect with output-shared full-range wavelength converters.

Figure 6 shows a logical recurrence for a  $2 \times 2/W-\lambda$   
20 twisted Benes wavelength-interchanging cross-connect.

Figure 7 shows a recursive construction of a  $[x_0, x_{F-1}]/[f_k, f_{k+W-1}], [f_1, f_{1+W-1}]$  twisted Benes wavelength-interchanging cross-connect.

Figure 8 shows a separable space-wavelength switch  
25 in accordance with the present invention.

Figure 9 shows an  $8 \times 8$  self-routing SW-Banyan topology in accordance with the present invention.

Figure 10 shows the application of the present invention transformation to networks based on horizontal  
30 extensions of an  $8 \times 8$  self-routing SW-Banyan network.

Figure 11 shows the application of the present invention transformation to a  $\log_2(8,1,2)$  network based on



an 8x8 SW-Banyan network.

Figure 12 shows a generic implementation of a wavelength interchanger in accordance with the present invention.

5        Figure 13 shows an implementation of a SW-Banyan self-routing wavelength interchanger in accordance with the present invention.

10        Figure 14 shows the switching states of a 2x2 switching element in accordance with the present invention.

Figure 15 shows the internal design of a 2x2 switching element in accordance with the present invention.

15        Figure 16 shows the internal design of a state changer for a partially connected network with 2x2 elements in accordance with the present invention.

Figure 17 shows a butterfly inter-stage connection module built with frequency-shifters in accordance with the present invention.

20        Figure 18 shows a generic frequency shuffler in accordance with the present invention.

Figure 19 shows a generic inverse frequency shuffler in accordance with the present invention.

25        Figure 20 shows an implementation of the 8x8 SW-Banyan network of Figure 9 in accordance with the present invention.

Figure 21 shows a state changer for the 8x8 SW-Banyan network of Figure 9 in accordance with the present invention.

30        Figure 22 shows an inter-stage connection module between stages 0 and 1 for the 8x8 SW-Banyan network of Figure 9 in accordance with the present invention.

Figure 23 shows an inter-stage connection module

between stages 1 and 2 for the 8x8 SW-Banyan network of Figure 9 in accordance with the present invention.

Figure 24 shows a  $\log_2(W, m, p)$  wavelength interchanger based on SW-Banyan wavelength interchangers in accordance with the present invention.

Figure 25 is a table containing the type of permutation used at each stage of several self-routing networks.

Figure 26 is a table containing the converter costs of a SW-Banyan wavelength interchanger in accordance with the present invention.

Figure 27 is a table containing the converter complexity of different self-routing wavelength interchangers in accordance with the present invention.

Figure 28 is a table containing the frequency shifter complexity of near-optimal  $\log_2(W, m, p)$  wavelength interchangers and associated separable wavelength-interchanging cross-connects in accordance with the present invention.

#### DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENT(S)

The present invention provides new architectures for wavelength-interchanging cross-connects based on wave-mixing converters. In these new architectures, the different switching domains are separated. The resulting cross-connect architecture comprises a central wavelength-selective cross-connect, and peripheral wavelength interchangers located at the inputs or outputs of the wavelength-selective cross-connect. The function of the wavelength-selective cross-connect is to switch channels spatially, while that of the wavelength interchangers is only to provide permutations of the

The present invention is focused on the internal design of wavelength interchangers. That is, the present

invention focuses on a wavelength interchanger architecture that shares some of the important characteristics of the multi-stage conversion design described in previous work. The common features are the use of bulk wavelength conversions in wave-mixing converters, and multi-stage wavelength conversions of individual wavelength channels. But the present invention also has multiple fundamentally new aspects. First, a new and more intuitive wavelength-to-space transformation is used. The principle of this transformation is to select some regular interconnection network and to assign the frequency  $f_{i \bmod W}$  to some inlet or outlet  $i$  in each switching stage. When starting from an interconnection network built out of  $2 \times 2$  elements, the transformation yields a logical network where each switching element has two different frequencies assigned to its two inlets or outlets. Also, in this logical representation, an outlet of some stage may connect to some inlet of the next stage, while the inlets and outlets are assigned different frequencies. Therefore, the new transformation leads to solutions where wavelength converters are needed to change the states of switching elements, and to provide inter-stage connection patterns.

At first glance, this new transformation appears to be less elegant and more costly (in terms of converter requirements) than previous transformations. However, this new transformation has the advantage of decoupling the design of switching elements from that of interstage

connection patterns. In addition to this advantage, this new transformation may also produce cost-effective wavelength interchangers (i.e., wavelength interchangers with a significantly lower converter complexity than previous designs). To meet this goal, a new physical implementation of the switching elements is provided, which allows the state of any switching elements to be changed at minimum converter costs. The key to this economical realization is to observe that each switching element processes adjacent frequencies (modulo  $W$ ). Assume that available frequencies are of the form  $f_i = f_0 + i\Delta f$ , where  $i = 0, \dots, W-1$ , and that each  $2 \times 2$  switching element processes some frequencies  $f_{2i}$  and  $f_{2i+1}$ , where  $i = 0, \dots, W/2-1$ . Some element may be changed from the bar to the cross-state by up-shifting  $f_{2i}$  by  $+\Delta f$ , and by down-shifting  $f_{2i+1}$  by  $-\Delta f$ . Then, for each stage, if a single pair of frequency shifting devices are used that are based on wave-mixing, and shifts in an amount of  $+\Delta f$  are provided to even frequencies, while shifts in an amount of  $-\Delta f$  are provided to odd frequencies, the state of any  $2 \times 2$  switching element in the stage can be changed.

In accordance with the present invention, a device containing frequency shifters and wavelength routers to selectively provide the frequency shifts to the different channels is called a *state changer*. Therefore, one state changer is needed for each switching stage, and the converter complexity of such a device is constant, and independent of  $W$ . Common interconnection networks have a number of stages of the order of the logarithm of their size. As a result, in the present invention architectures, the expected converter costs for all the required state changers is  $O(\log_2 W)$ . The present invention

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technique also requires wavelength conversions to be provided for inter-stage connection patterns. Usual connection patterns, such as shuffles or butterfly permutations, have interesting arithmetic properties that are exploited in accordance with the present invention to reduce converter costs. For example, in the case of a butterfly permutation, a sequence of  $w$  bits such as  $b_{w-1}...b_{h+1}b_hb_{h-1}...b_0$  is mapped to  $b_{w-1}...b_{h+1}b_0b_{h-1}...b_h$ , where  $h$  is an integer specific to the butterfly permutation. In other words, for a given  $h$ , the butterfly permutation simply swaps the bit in position 0 and the bit in position  $h$ . In the wavelength domain, the butterfly permutation maps some frequency  $f_i = f_0 + i\Delta f$ , such that  $b_{w-1}...b_{h+1}b_hb_{h-1}...b_0$  is the binary representation of  $i$ , to the frequency  $f_j = f_0 + j\Delta f$ , such that  $b_{w-1}...b_{h+1}b_0b_{h-1}...b_h$  is the binary representation of  $j$ . The butterfly permutation can be implemented with few converters by exploiting the following key observations on the permutation:

- 1.) Frequencies  $f_i$  such that the binary representation of  $i$  is either of the form  $b_{w-1}...b_{h+1}0b_{h-1}...b_10$  or  $b_{w-1}...b_{h+1}1b_{h-1}...b_11$  are left unchanged;
- 2.) Frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}1b_{h-1}...b_10$  are translated by  $-(2^h-1)\Delta f$ ; and
- 3.) Frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}0b_{h-1}...b_11$  are translated by  $+(2^h-1)\Delta f$ .

Therefore, between any two switching stages, butterfly frequency permutations can be implemented with a pair of frequency shifting devices providing frequency shifts in the amount of  $-(2^h-1)\Delta f$  or  $+(2^h-1)\Delta f$ . As before, some butterfly inter-stage connections may be provided

with a constant number of all-optical converters,  
independent of the number  $W$  of frequencies. Other  
important permutations such as shuffles and inverse  
shuffles are described next. For a given  $0 \leq h \leq w-1$ , the  
5 shuffle  $\sigma_h$  does a right-to-left circular permutation of  
the last  $h+1$  bits of any sequence of binary digits. In  
other words,  $\sigma_h$  maps any sequence  $b_{w-1}b_{w-2}...b_0$  to  
 $b_{w-1}...b_{h+1}b_{h-1}...b_0b_h$ . For the same  $h$ , an inverse shuffle  
permutation is simply the inverse permutation of the  
10 shuffle  $\sigma_h$ . Therefore, the corresponding inverse shuffle  
permutation is denoted by  $\sigma_h^{-1}$ . The permutation  $\sigma_h^{-1}$  maps  
some binary sequence  $b_{w-1}b_{w-2}...b_0$  to  $b_{w-1}...b_0b_h...b_1$ . For a given  
 $0 \leq h \leq N-1$ , both types of permutations may be conveniently  
described with constrained increasing frequency mappings  
15 (see related U.S. Patent Application No. \_\_\_\_\_  
(Attorney Docket No. 57983-000012, Client Reference No.  
12867RO) referenced above). In a system with  $W=2^w$   
frequencies of the form  $f_i = f_0 + i\Delta f$ , specific sets of  
frequencies are considered and denoted by  $\Phi^h$  where  
20  $0 \leq h \leq w-1$ . For a given value of  $h$ , the set  $\Phi^h$  contains all  
the frequencies such that the  $h$ -th least significant  
digit of the binary representation of their index is  
null. In other words, a frequency  $f_i$  belongs to  $\Phi^h$  if the  
binary representation of  $i$  is  $b_{w-1}...b_0$ , where  $b_h = 0$ . Then the  
25 mapping  $\Gamma_h$  is introduced such that some input frequency  
$$f_i = f_0 + \Delta f \left( \sum_{l=0}^{w-1} 2^l b_l \right) \text{ in } \Phi^h \text{ is mapped to } \Gamma_h(f_i) = f_0 + \Delta f \left( \sum_{l=h+1}^{w-1} 2^l b_l + 2 \sum_{l=0}^h 2^l b_l \right)$$
  
in  $\Phi^0$ , where  $b_{w-1}...b_0$  is the binary representation of  $i$ . The  
mapping  $\Gamma_h$  is an increasing up-conversion according to  
related U.S. Patent Application No. \_\_\_\_\_ (Attorney

Docket No. 57983-000012, Client Reference No. 12867RO)  
referenced above.

The inverse mapping of  $\Gamma_h$  is also considered, which  
is denoted as  $\Gamma_h^{-1}$ . The mapping  $\Gamma_h^{-1}$  maps some input

5 frequency  $f_j = f_0 + \Delta f \left( \sum_{l=0}^{w-1} 2^l b_l \right)$  in  $\Phi^0$  to

$$\Gamma_h^{-1}(f_j) = f_0 + \Delta f \left( \sum_{l=h+1}^{w-1} 2^l b_l + \frac{1}{2} \sum_{l=0}^h 2^l b_l \right) \text{ in } \Phi^h, \text{ where } b_{w-1} \dots b_0 \text{ is the}$$

binary representation of  $j$ . It is easy to see that the  
inverse mapping  $\Gamma_h^{-1}$  is an increasing down-conversion  
according to related U.S. Patent Application No.

10 \_\_\_\_\_ (Attorney Docket No. 57983-000012, Client  
Reference No. 12867RO) referenced above.

Assuming that for some frequency  $f_i = f_0 + i\Delta f$  the binary  
representation of  $i$  is  $b_{w-1} \dots b_0$ . The shuffle  $\sigma_h$  is  
implemented with the increasing frequency up-conversion  
15 mapping  $\Gamma_h$  as follows:

- 1.) For any frequency  $f_i$  such that  $b_h = 0$ ,  $\sigma_h(f_i) = \Gamma_h(f_i)$ ; and
- 2.) For any frequency  $f_i$  such that  $b_h = 1$ ,  
 $\sigma_h(f_i) = \Gamma_h(f_i - 2^h \Delta f) + \Delta f$ .

Similarly, the inverse shuffle  $\sigma_h^{-1}$  is implemented  
20 with the increasing frequency down-conversion mapping  $\Gamma_h^{-1}$   
as follows:

- 1.) For any frequency  $f_i$  such that  $b_0 = 0$ ,  $\sigma_h^{-1}(f_i) = \Gamma_h^{-1}(f_i)$ ; and
- 2.) For any frequency  $f_i$  such that  $b_0 = 1$ ,  
 $\sigma_h^{-1}(f_i) = \Gamma_h^{-1}(f_i - \Delta f) + 2^h \Delta f$ .

25 In related U.S. Patent Application No. \_\_\_\_\_  
(Attorney Docket No. 57983-000012, Client Reference No.  
12867RO) referenced above, it is described how to  
implement constrained increasing up-conversion or down-

conversion mappings with  $O(\log_2 W)$  wave-mixing converters. Overall, many interconnection networks may be built out of  $2 \times 2$  elements, which either use butterfly or shuffle inter-stage connection patterns and have a logarithmic converter complexity. The theory of multi-log networks allows self-routing, non-blocking or rearrangeably non-blocking wavelength-interchangers to be designed in accordance with the present invention with a converter complexity of  $O(F(\log W)^n)$ , where  $n$  is a small constant integer (typically 1,2,3) independent of the number of frequencies, and of the number of fibers. It is a significant improvement over previous designs with converter complexities of  $O(FW)$ .

I. All-Optical Wavelength Conversion

To give a brief overview of all-optical conversion techniques, it is noted that there are two major types of all-optical wavelength converters. The first type is based on optical gating, while the second type is based on wave-mixing effects in nonlinear media (see S. Yoo, "Wavelength-conversion technologies for WDM network applications", IEEE Journal of Lightwave Technology, vol. 14, pages 955-966, June 1996). These different devices are described below in more detail.

A. Optical Gating Converters

Optical gating converters include converters using cross-gain modulation in semiconductor optical amplifiers (see S. Yoo referenced above). They operate by translating signals carried on some input frequency to another frequency that plays the role of the pump, in the saturation regime of semiconductor optical amplifiers.



These converters can only convert the carrier frequency of one input signal at a time. However, they can map different carrier frequencies to the same pump frequency. Referring to Figure 1, there is shown an exemplary  
5 optical-gating wavelength converter 10 for translating an input signal carried on an input frequency,  $f_{in}$ , to an output signal with a carrier frequency equal to the pump frequency, i.e.  $f_{out} = f^p$ .

10 B. Wave-Mixing Converters

Wave-mixing converters exploit nonlinear effects in appropriate medias such as optical fibers or semiconductor optical amplifiers. A variety of nonlinear effects exist including difference-frequency generation,  
15 and four wave-mixing (see S. Yoo referenced above). Converters of this type usually have a precise parametric relationship between the incoming frequencies, the pump and the outgoing frequencies. In the case of difference-frequency generation with some pump frequency  $f^p$ , an  
20 input frequency  $f$  is mapped to the output frequency  $f^p - f$  (see Figure 2, which shows a wave-mixing wavelength converter 20 based on difference-frequency generation). Major advantages of wave-mixing converters are their high level of transparency and their ability to simultaneously  
25 convert several input frequencies.

C. Frequency Shifters

For purposes of this detailed description, a frequency shifter may be any device that performs some  
30 frequency translation by some amount  $\Delta$ , where  $\Delta$  is independent of the input frequency. Such a device maps any input signal on some carrier frequency  $f$  to another

signal on the carrier frequency  $f+\Delta$ .

Referring to Figure 3, there is shown a frequency shifter 300 wherein frequency translation is implemented with two cascaded converters based on difference-  
5 frequency generation (DFG). That is, frequency shifter 300 comprises two cascaded difference-frequency generation wave-mixers 303 and 306 driven by different pump frequencies 302 and 304. Outgoing frequencies 307  
10 are the result of the translation of incoming frequencies 301 by an amount equal to the difference of the pump frequencies in the second and the first wave-mixing devices.

## II. Designs of All-optical Cross-Connects

15 According to the placement of wavelength conversions in a switch, two classes of wavelength-interchanging cross-connects are distinguished. The first class of solutions provide wavelength conversion in a single stage, often the input or the output stage of a  
20 wavelength-selective cross-connect (see B. Ramamurthy et al. referenced above and K. Lee and V. Li, "A frequency-convertible optical network", IEEE Journal of Lightwave Technology, vol. 11, pages 962-970, May-June 1993). The second class of solutions perform wavelength conversions  
25 in several stages (see N. Antoniades referenced above). Single-stage approaches provide the best transmission performance at the expense of high converter costs, while multi-stage conversion architectures have poorer transmission performance, but require significantly fewer  
30 wavelength-converters.

### A. Single-Stage Approach

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Single-stage wavelength conversion is the most popular solution to design wavelength-interchanging cross-connects (see B. Ramamurthy referenced above). In this approach, the basic principle is to allocate a number of wavelength converters to the inputs or to the outputs of a wavelength-selective cross-connect (see B. Ramamurthy referenced above). This technique does not perform cascaded wavelength conversions on the switched optical signals. Therefore, it minimizes transmission impairments due to all-optical wavelength conversions. However, this method often requires large numbers of converters, and it results in high switch costs. When the number of converters is equal to the number of inputs or outputs, converters can be dedicated to inputs or to the outputs. Otherwise, the available converters must be shared among all channels. In the first case, an input/output dedicated converter solution is obtained (see B. Ramamurthy referenced above), while in the second case, an input/output shared converter solution is obtained (see K. Lee et al. referenced above and K. Lee and V. Li, "Optimization of a WDM optical packet switch with wavelength-converters", in Proceedings of IEEE INFOCOM'95, vol. 2, pages 423-430, April 1995). These two approaches are now described in more detail.

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1. Input/Output Dedicated Wavelength Conversion

Input (or output) dedicated wavelength conversion assigns a wavelength-converter to each input (or output) of a wavelength-selective cross-connect. In a system with  $F$  fibers, and  $W$  wavelengths per fiber, this approach requires a total number of converters equal to  $FW$ . In this technique, the blocking performance of the cross-connect directly depends on the conversion range of the

converters, and on the blocking performance of the wavelength-selective cross-connect that are used. When the wavelength-selective cross-connect is strictly non-blocking, and the converters have full-range (i.e., they  
5 can change the frequency of any incoming signal to any other frequency) a strictly non-blocking wavelength-interchanging cross-connect is obtained.

Referring to Figure 4, there is shown the generic architecture of a wavelength-interchanging cross-connect  
10 based on output-dedicated wavelength-converters. A central wavelength-selective cross-connect 400 performs the function of space-switching, while dedicated converters like 401 provide wavelength-conversion.

15 2. Input/Output Shared Wavelength Conversion

Large converter requirements have prompted the development of input (or output) shared wavelength converters, where a number of inputs (or outputs) of a wavelength-selective cross-connect share a converter pool  
20 that contains a number of converters strictly smaller than the number of inputs (or outputs) (see K. Lee et al. referenced above). In this case, a routing and frequency assignment algorithm allocates converters from the pool to minimize the blocking probability of the cross-  
25 connect. Empirical results suggest that in certain network scenarios, there is a quick saturation in the improvement of the blocking probability, when the number of shared converters exceed certain thresholds (see K. Lee et al. referenced above). In other words, a small  
30 number of shared converters may provide most of the benefits of wavelength-conversion.

Referring to Figure 5, there is shown a the generic architecture of a wavelength-interchanging cross-connect

based on input/output shared wavelength-converters. The central wavelength-selective cross-connect 500 provides two functions. First it switches channels in the space division. Second, when required the optical space switch  
5 500 directs channels to one of the shared converters in the pool 501. The converted channels are also switched to their output fibers by the central cross-connect 500.

In spite of the above-mentioned advantages, many questions remain about designs based on single-stage  
10 shared wavelength-conversion . First, there is little knowledge about the precise quantitative relationship between the blocking probability, the number of shared converters, and the particular routing and frequency assignment algorithm used by the wavelength-interchanging  
15 cross-connect. Second, single-stage shared converters have been mostly designed for wavelength division multiplexing access networks, and they do not provide a way to generate interconnection with desirable blocking properties (i.e., self-routing, non-blocking,  
20 rearrangeable or wide-sense non-blocking).

#### B. Multi-Stage Approach

Unlike single-stage methods, multi-stage techniques perform several intermediate wavelength conversion  
25 operations. Until the development of wave-mixing converters with bulk channel conversion capacities (see S. Yoo referenced above), multi-stage wavelength conversion was not a practical technique. Wave-mixing converters are still in their experimental phase, but  
30 earlier studies have already shown how these devices can help the design of rearrangeably non-blocking wavelength-interchanging cross-connects (see N. Antoniadis et al. referenced above).

To design an optical cross-connect with  $F$  fibers and  $W$  frequencies per fiber, which can be denoted by  $F \times F/W - \lambda$ , a recursive construction of Benes switches is used, as shown in Figure 6. In a multi-frequency multi-fiber system, a channel is denoted by  $(f_i, x_j)$ , where the channel frequency is  $f_i$  and its fiber is  $x_j$ . For a system with  $F=2$  fibers and  $W$  frequencies per fiber, this method comprises assigning the wavelength channels to each switch element 602 of the first and last stages as follows:

- 1.) For each switch element  $i$ , where  $i \leq (W-1)/2$ : channel  $(f_i, x_0)$  600 is assigned to each top inlet or outlet of the switch element, while channel  $(f_i, x_1)$  605 is assigned to each bottom inlet or outlet of the same element.
- 2.) For each switch element  $i$ , where  $i \leq (W-1)/2$ : channel  $(f_{W-1-i}, x_1)$  601 is assigned to each top inlet or outlet of the switch element, while channel  $(f_{W-1-i}, x_0)$  606 is assigned to each bottom inlet or outlet of the same element.

Each switch element in the first (or last) stage connects by its top outlet (or inlet) to a top  $2 \times 2/(W/2) - \lambda$  Benes middle stage switch 603, and by its bottom outlet (or inlet) to a bottom  $2 \times 2/(W/2) - \lambda$  Benes middle stage switch 604. The design of both middle stage switches is known (see N. Antoniadis et al. referenced above).

The top middle stage switch 603 processes the frequencies in the interval  $[f_0, f_{W/2-1}]$  for all the incoming fibers, while the bottom middle stage switch 604 processes the frequencies in the interval  $[f_{W/2}, f_{W-1}]$  for all the incoming fibers.

Referring to Figure 7, there is shown a recursive construction of a  $[x_0, x_{F-1}]/[f_k, f_{k+W-1}], [f_1, f_{1+W-1}]$  twisted

[illegible]

The multi-stage method described above enables the design of rearrangeably non-blocking wavelength-interchanging cross-connects, which require at most  $FW/2$  single or dual pump difference-frequency generation converters, instead of twice that number as would be obtained with other approaches. Therefore, significant



The benefits of the above-described multi-stage method are counter-balanced by drawbacks inherent to the rearrangeably non-blocking nature of the switch. Indeed, it is impractical to consider rerouting ongoing optical circuits because of the high volumes of traffic carried by the circuits and of the absence of all-optical buffers. To guarantee the quality of service of optical circuits, a better solution is to consider strictly non-blocking cross-connects or wavelength interchangers. A natural approach to build strictly non-blocking switches is the vertical replication of given rearrangeably non-blocking switches. For example, the Cantor network is a strictly non-blocking interconnection which is built by vertically stacking  $\log_2 M$  copies  $M \times M$  Benes networks, where  $M$  is the size of the Cantor network. When the vertical stacking philosophy is applied to the above-described multi-stage method for a cross-connect with  $F$  fibers, and  $W$  frequencies per fiber, a strictly non-blocking frequency-interchanging cross-connect is obtained with a converter complexity of  $F.W.\log_2(F.W)/2$ . When  $F.W$  the total number of wavelength channels is strictly larger than 4, the converter complexity is larger than the complexity of the previously discussed dedicated converter solutions. To overcome this problem, a new technique is needed to design wavelength-interchanging cross-connects, with smaller converter requirements.

30       The benefits of the above-described solutions  
provide a motivation to investigate other architectures  
based on multi-stage wavelength-conversions, and on wave-

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mixing converters. However, the present invention  
technique differs from these existing solutions in many  
respects. First, a three-stage separable space-wavelength  
switching approach is considered, where switching is  
5 first in the wavelength domain, then in the space  
dimension, and then again in the wavelength domain. In  
previous described solutions, a joint technique is used  
where channels are simultaneously switched in all  
domains, at each stage. A second major difference is a  
10 new space-wavelength transformation that is more  
intuitive than those described above. Thirdly, a set of  
new devices is presented based on wave-mixing frequency-  
shifters, which enable the translation of the present  
invention space-wavelength transformation into physical  
15 implementations at logarithmic converter costs. In the  
following sections, a WDM system with  $W=2^m$  optical  
frequencies of the form  $f_i = f_0 + i\Delta f$  is assumed.

#### A. Separable Space-Wavelength Switches

20 A separable space-wavelength switch does not switch  
channels in the space and wavelength domains  
simultaneously. Such a wavelength-interchanging cross-  
connect usually comprises a space-switch equipped with  
wavelength interchangers (WI) located at its input or at  
25 its outputs, as shown in Figure 8. That is, Figure 8  
shows a separable space-wavelength switch wherein  $F$   
incoming fibers 801 each carry  $W$  wavelength channels.  
Individual space-wavelength channels are switched by the  
wavelength-selective cross-connect (WSXC) 800. Wavelength  
30 interchangers (WI) like 802 and 803 are dedicated to each  
input/output fiber and provide frequency permutations of  
the incoming or outgoing channels.

The class of separable wavelength-interchanging cross-connects includes switches that use atomic wavelength conversions of channels, and dedicated wavelength converters, at inputs or outputs. However, wavelength interchangers that are internally based on multi-stage wavelength conversions may also be used. A natural step is to consider wavelength interchangers obtained by simplification of the above-described

B. New Transformation

15        The present invention provides a new frequency-space transformation. This new frequency-space transformation is applicable to partially or to fully connected interconnection networks. The transformation simply consists of labeling some inlet or outlet  $i$  of any

20        switching stage with the carrier frequency  $f_{i \bmod W}$ . In spite of the generality of the transformation, this detailed description focuses on the following types of network topologies:

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1. Self-Routing Networks

A self-routing interconnection network provides a unique path for any input-output pair. Banyan type networks form a large subclass within the set of self-routing interconnection topologies. A Banyan type self-routing network of size  $N$  usually has  $n = \log_2 N$  consecutive stages, where each stage contains  $N/2$   $2 \times 2$  switching elements. The inlets and outlets of adjacent stages are connected to one-another by specific inter-stage connection patterns. To describe these patterns, assume that the inlets and outlets of each stage are numbered from 0 to  $N-1$ , and the index of each inlet or outlet is described by its binary representation over  $\log_2 N$  digits. Then, it is possible to describe Banyan type inter-stage connection patterns as follows:

- 1.) Butterfly pattern  $\beta_h$ ,  $1 \leq h \leq n-1$ : some outlet  $i$  with binary representation  $b_{n-1} \dots b_{h+1} b_h b_{h-1} \dots b_0$  connects to inlet  $j$  with binary representation  $b_{n-1} \dots b_{h+1} b_0 b_{h-1} \dots b_h$  in the next switching stage.
- 2.) Shuffle pattern  $\sigma_h$ ,  $1 \leq h \leq n-1$ : some outlet  $i$  with binary representation  $b_{n-1} \dots b_{h+1} b_h b_{h-1} \dots b_0$  connects to inlet  $j$  with binary representation  $b_{n-1} \dots b_{h+1} b_{h-1} \dots b_0 b_h$  in the next switching stage.
- 3.) Inverse shuffle pattern  $\sigma_h^{-1}$ ,  $1 \leq h \leq n-1$ : some outlet  $i$  with binary representation  $b_{n-1} \dots b_{h+1} b_h b_{h-1} \dots b_0$  connects to inlet  $j$  with binary representation  $b_{n-1} \dots b_{h+1} b_0 b_h \dots b_1$  in the next switching stage.
- 4.) The identity pattern  $j$  maps any outlet to the inlet with the same index in the next stage.

Referring to Figure 25, there is provided a table of

common self-routing networks wherein the type of permutation used at each stage is described. That is, in the table of Figure 25, a notation of the type  $P(h)$  indicates the pattern used between stage  $h$  and stage  $h+1$ .  
5  $P(0)$  and  $P(n)$  are the permutations that are respectively applied to the inputs and to outputs of the interconnection network.

When the present invention transformation is applied to Banyan type self-routing networks, distinct  
10 frequencies are assigned to each row of inlets and outlets in the switch. Figure 9 shows an example of this transformation for a SW-Banyan network. That is, Figure 9 shows an 8x8 self-routing SW-Banyan topology. As can be seen from Figure 9, each switching element 900 switches  
15 two adjacent frequencies, and inter-stage connections also involve some amount of wavelength conversion. In the example of Figure 9, the dashed grey lines represent the logical inter-stage connections that imply wavelength conversion. Thus, the following general conclusions may  
20 be drawn when the present invention transformation is applied to partially connected networks with an identical number of inlets and outlets in each stage:

- 1.) Each switching element switches a set of distinct frequencies. In a given stage, the different frequency  
25 sets assigned to the switching elements form a partition of the frequency spectrum; and
- 2.) Some inter-stage connections require wavelength conversions.

In the following section, some background is  
30 provided on multi-log networks.

## 2. Multi-Log Networks

Self-routing networks are interesting when they

allow distributed high-performance routing in packet switches. However, they suffer from blocking. Two techniques are available to address this problem. The first technique is named *horizontal extension*, and it consists in appending additional stages (see A. Pattavina referenced above). These stages are obtained by mirroring some of the stages of the original self-routing network. The Benes network is a good example of this technique, and it is obtained by the horizontal extension of the reverse Baseline network with its last  $\log_2 N - 1$  stages, where the size of the switch is  $N \times N$ . Figure 10 shows the application of the present invention transformation to networks based on horizontal extensions of an  $8 \times 8$  self-routing SW-Banyan network.

The second technique is called *vertical replication* (also see A. Pattavina referenced above). Its principle is to stack identical copies of some partially connected network that may be a self-routing network, or a modification of such a network through the technique of horizontal extension. An example of application of the method of vertical replication is the Cantor network that is obtained by vertically stacking  $\log_2 N$  copies of  $N \times N$  Benes networks. When horizontal extension and vertical replication are combined, self-routing networks can be transformed into topologies belonging to the general class of multi-log networks. Multi-log networks are also called  $\log_2(N, m, p)$  networks, where  $N$  is the size of the network,  $m$  is the number of stages appended to the original self-routing network, and  $p$  is the number of vertically stacked copies. The blocking properties of  $\log_2(N, m, p)$  networks are given by two fundamental results:

- 1.) A  $\log_2(N, m, p)$  network is rearrangeably non-blocking

if  $p \geq 2^{\frac{n-m}{2}}$ , where  $n = \log_2 N$

2.) A  $\log_2(N, m, p)$  network is strictly non-blocking if

$$p \geq \begin{cases} 2^{\frac{3}{2} \cdot \frac{n-m}{2} + m - 1}, & n+m \text{ even} \\ 2^{\frac{n-m+1}{2} + m - 1}, & n+m \text{ odd} \end{cases}, \text{ where } n = \log_2 N.$$

When  $p=1$ , a stronger result is obtained concerning  
5  $\log_2(N, m, 1)$  networks built out of SW-Banyan self-routing  
networks. It states that these networks become  
rearrangeably non-blocking if  $m=n-1$ .

The present invention transformation may also be  
applied to  $\log_2(N, m, p)$  networks. When we have only one  
10 copy ( $p=1$ ), the resulting logical network has the same  
characteristics as in the case of self-routing networks:  
1.) Each switching element switches a set of distinct  
frequencies. In a given stage, the different frequency  
sets assigned to the switching elements form a partition  
15 of the frequency spectrum; and  
2.) Some inter-stage connections require wavelength  
conversions.

When at least two copies ( $p>1$ ) are present, an  
important difference resides in the fact that in some  
20 stages as many as  $p$  different inlets or outlets may be  
assigned the same frequency. Figure 11 shows the  
application of the present invention transformation to a  
 $\log_2(8, 1, 2)$  network based on an  $8 \times 8$  SW-Banyan network.

#### 25 C. Implementation of Self-Routing Wavelength Interchangers

As described above, when applying the present  
invention wavelength-to-space transformation to a self-  
routing network, a logical topology is obtained where



logical 2x2 elements switch two signals carried on two adjacent frequencies, and inlets and outlets assigned possibly different frequencies are connected by the inter-stage connection patterns. These two

5 characteristics of the present invention transformation both imply the use of wavelength conversion to provide the two following functions:

- 1.) Definition of the states of the switching elements. In the bar state individual elements need not modify the frequencies of incoming signals. But in the cross state, the frequencies of incoming signals must be swapped.
- 10 2.) Inter-stage connections: When an inlet assigned a first frequency in a given stage connects to an outlet assigned a second frequency in the following stage, such that the two frequencies are different, the frequency of the signal coming from the inlet must be converted to the frequency assigned to the outlet.
- 15

Thus, a generic implementation for self-routing wavelength interchangers is proposed in accordance with the present invention, where these two types of wavelength conversion needs are separately considered. This separation allows for a more intuitive and modular design. Then converter requirements for the different types of conversion needs may be optimized separately.

20

25 Wavelength conversions corresponding to changes in the states of switching elements are provided by a new device called a *state changer*. In a given stage, the state changer is shared by all switching elements. The only function of the state changer is to change the frequency of incoming signals as follows:

30

- 1.) From  $f_{2i}$  to  $f_{2i+1}$  for signals on a carrier frequency with an even index;

The wavelength conversions required for inter-stage connections are implemented by another type of device called an *inter-stage connection module*. Both state changers and inter-stage connection modules provide predetermined frequency mappings, regardless of the state of the switch. In other words, signals on some given input carrier frequency are always moved to the same output carrier frequency by state changers and inter-stage connection modules, although these two modules may select different output carrier frequencies for the same input carrier frequency. In the case the state changer, the predetermined frequency mapping always maps each even frequency to the higher adjacent odd frequency, and each odd frequency to the smaller adjacent even frequency. In the case of interstage connection modules, the predetermined frequency mapping is fixed and based upon the interstage connection pattern provided by the module.

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(SC) enables changes in the switching states of elements by swapping the carrier frequencies of signals switched by a common element. In Figure 12, the specific topology implemented by the architecture depends on the nature of  
5 the frequency permutation implemented by the inter-stage connection modules.

The implementation of a SW-Banyan self-routing wavelength interchanger is shown in Figure 13. In this implementation, it can be seen that the frequency  
10 permutation in some stage  $h \leq w-1$  is the butterfly permutation  $\beta_h$ , as shown in inter-stage connection module (ISCM) 1301. This is consistent with the above description of the SW-Banyan self-routing network in the table of Figure 25.

15 After providing generic designs for wavelength interchangers, it is now appropriate to propose efficient ways to implement state-changers, and inter-stage connection modules, with few converters.

## 20 1. Switching Elements

In the present invention architecture, each switching element (SE) switches signals on adjacent carrier frequencies. In the bar state, a switching element (SE) does not modify the frequencies of incoming  
25 signals. However, in the cross state, a switching element (SE) swaps the carrier frequencies of incoming signals, as shown in Figure 14.

Referring to Figure 15, the internal design of a 2x2 switching element is shown. It takes two inputs at  
30 carrier frequencies  $f_i$  and  $f_{i+1}$ . The state of the element is given by the state of a 2x4 wavelength-selective cross-connect 1500. In the bar state, the top and bottom

input signals are respectively routed to the first and to the second output, in the output set 1501. In the cross state, the top and bottom input signals are respectively routed to the third and to the fourth output, in the set 1502. Two combiners 1503 and 1504 produce two outputs carrying signals on adjacent frequencies, by combining the signals that come directly from the cross-connect 1500 in the output set 1501 and those that come from the state changer in the output set 1505. The first combiner 1503 takes two inputs, its first and second inputs respectively correspond to the first output of the cross-connect and to the output from the state changer dedicated to frequency  $f_i$ . The second combiner 1504 takes two inputs, its first and second inputs respectively correspond to the second output of the cross-connect and to the output from the state changer dedicated to frequency  $f_{i+1}$ .

Therefore, each switching element is essentially a space switch, and relies on state changers to provide the frequency-swapping function that is implied when it is in the cross state. In combination with state changers, switching elements provide a dynamic frequency mapping (keep or swap incoming frequencies). This mapping is determined by some wavelength-routing algorithm adapted to the wavelength-interchanger, and by the overall permutation of frequencies realized by the wavelength-interchanger. More specific implementation details concern the choice of a solution for the 2x4 wavelength-selective cross-connect. The choices include micro-electromechanical devices and directional couplers.

## 2. State Changer

In the present invention design, the function of each state changer is to provide a predetermined fixed frequency-mapping regardless of the state of the switch. This mapping is the following for any  $i \leq W/2 - 1$ :

5    1.)     $f_{2i} \rightarrow f_{2i+1} = f_{2i} + \Delta f$

2.)     $f_{2i+1} \rightarrow f_{2i} = f_{2i+1} - \Delta f$

That is, even frequencies are translated by  $+\Delta f$ , while odd frequencies are translated by  $-\Delta f$ . Such an observation leads to the implementation presented in Figure 16. That is, Figure 16 shows the internal design of a state changer for a partially connected network with  $2 \times 2$  elements, wherein each switch element in the stage sends two signals at optical frequencies of the form  $f_{2i}, f_{2i+1}$  into the state changer input 1100. The input frequencies are processed by a first wavelength router 1101 to separate even from odd frequencies. Odd frequencies are decreased by  $-\Delta f$  in the frequency shifter 1105. Even frequencies are increased by  $+\Delta f$  in the frequency shifter 1102. Finally, all the shifted frequencies are processed by a second wavelength router 1106 to isolate the frequencies assigned to the different switching elements of the stage.

Frequencies are grouped into  $W/2$  outputs 1103 that are sent to the appropriate switching elements. This implementation relies on transparent frequency shifters. One option to build these shifters is to cascade two difference-frequency generation wave-mixers driven by different pump frequencies, as described above with reference to Figure 3. The wavelength-routers 1101 and 1106 may be built using several technologies such as, for example, arrayed waveguide gratings, dielectric thin films and fiber-bragg gratings.

Regardless of the choice made, it is important to observe that the number of frequency shifters is independent of the number of frequencies. Therefore, in a self-routing Banyan network, state changers can be  
5 implemented with a wavelength converter cost of  $O(\log_2 W)$ . Based on this estimate, state-changers are expected to have a minimum contribution on the overall converter complexity of the wavelength interchanger. In the following sections, it is shown how it is possible to  
10 build inter-stage connection modules corresponding to butterfly or shuffle frequency permutations, which either have a constant or a logarithmic converter complexity.

### 3. Butterfly Inter-Stage Connection Module

15 In the wavelength domain, the butterfly permutation maps some frequency  $f_i = f_0 + i\Delta f$ , such that  $b_{w-1}...b_{h+1}b_hb_{h-1}...b_0$  is the binary representation of  $i$ , to the frequency  $f_j = f_0 + j\Delta f$ , where  $b_{w-1}...b_{h+1}b_0b_{h-1}...b_h$  is the binary representation of  $j$ . Therefore for some given  $h=0,...,w-1$ , the butterfly  
20 permutation implements a predetermined fixed frequency mapping. This mapping has the following interesting properties:

- 1.) Frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}0b_{h-1}...0$  or  $b_{w-1}...b_{h+1}1b_{h-1}...1$  are left  
25 unchanged.
- 2.) Frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}1b_{h-1}...0$  are down-shifted by  $-(2^h-1)\Delta f$ .
- 3.) Frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}0b_{h-1}...1$  are up-shifted by  $+(2^h-1)\Delta f$ .

30 Thus, for some given  $h=0,...,w-1$  a butterfly inter-stage connection module may be implemented with two

frequency-shifters of  $+(2^h-1)\Delta f$  and  $-(2^h-1)\Delta f$ , and with wavelength-selective components. These wavelength-selective components selectively simply need to route each frequency  $f_i$  to the different shifters according to the relative values of the  $h+1$ -th least significant digit (bit  $b_h$ ), and that of the least significant digit (bit  $b_0$ ), in the binary representation of the frequency index  $i$ , as it is shown in Figure 17. That is, Figure 17 shows a butterfly inter-stage connection module built with frequency-shifters, wherein a first wavelength router 1700 groups the frequencies into four disjoint sets as follows:

- 1.) A first set 1707 contains frequencies  $f_i$  such that the binary representation of  $i$  is of the form  
15  $b_{w-1}...b_{h+1}0b_{h-1}...0$ .
- 2.) A second set 1706 contains frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}1b_{h-1}...1$ .
- 3.) A third set contains frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}0b_{h-1}...1$ .
- 20 4.) A fourth set 1705 contains frequencies  $f_i$  such that the binary representation of  $i$  is of the form  $b_{w-1}...b_{h+1}1b_{h-1}...0$ .

Frequencies in the first set 1707 and in the second set 1706 are directly sent to wavelength router 1702.

25 Frequencies in the third set 1704 are translated by  $+(2^h-1)\Delta f$  in frequency shifter 1703, and then sent to wavelength router 1702. Frequencies in the fourth set 1705 are translated by  $-(2^h-1)\Delta f$  in frequency shifter 1701, and then sent to wavelength router 1702. The function of

30 the wavelength router 1702 is to direct the incoming frequencies to the proper switching elements in the next

stage. When it comes to the practical implementation of the module, there are many choices concerning the nature of the wavelength routers 1700 and 1702, and the realization of the frequency shifters. For the wavelength  
5 routers, the choice of techniques mentioned above with respect to the wavelength routers used in state changers (i.e., arrayed waveguide gratings, dielectric thin films, and fiber bragg gratings) are available. However, the complexity of the routing function leads to preferably  
10 selecting arrayed waveguide gratings over the other techniques. As for the frequency shifters, they may be implemented with cascaded wavelength converters based on difference-frequency generation, as mentioned above.

In the design of Figure 17, the converter complexity  
15 of a butterfly inter-stage connection module is constant and independent of the number of frequencies. Therefore, all inter-stage connection modules that are required in a self-routing SW-Banyan network may be provided with logarithmic converter complexity.

20

#### 4. Shuffle and Inverse-Shuffle Inter-Stage Connection Modules

Frequency shuffle and inverse frequency shuffle permutations are implemented with the help of specific  
25 mappings called constrained increasing frequency-mappings. Regarding these mappings, detailed discussions of their properties and of their implementation with  $O(\log_2 W)$  frequency-shifters is provided in the related U.S. Patent Application No. \_\_\_\_\_ (Attorney Docket No.  
30 57983-000012, Client Reference No. 12867RO). Both frequency-shuffle and inverse-frequency shuffle interstage connection modules provide fixed frequency



mappings regardless of the state of the wavelength-interchanger. For a given  $0 \leq h \leq w-1$ , the shuffle  $\sigma_h$  does a right-to-left circular permutation of the last  $h+1$  bits of any sequence of binary digits. In other words,  $\sigma_h$  maps any sequence  $b_{w-1}b_{w-2}...b_0$  to  $b_{w-1}...b_{h+1}b_{h-1}...b_0b_h$ . For a given  $0 \leq h \leq w-1$ , the inverse shuffle permutation is simply the inverse permutation of the shuffle  $\sigma_h$ , and is therefore denoted by  $\sigma_h^{-1}$ . The permutation  $\sigma_h^{-1}$  maps some binary sequence  $b_{w-1}b_{w-2}...b_0$  to  $b_{w-1}...b_0b_h...b_1$ . In the wavelength domain, both types of permutations may be conveniently described with increasing frequency-mappings (see related U.S. Patent Application No. \_\_\_\_\_ (Attorney Docket No. 57983-000012, Client Reference No. 12867RO) referenced above).

In a system with  $W=2^w$  frequencies of the form  $f_i = f_0 + i\Delta f$ , specific sets of frequencies are considered and denoted by  $\Phi^h$  where  $0 \leq h \leq w-1$ . For a given value of  $h$ , the set  $\Phi^h$  contains all the frequencies such that the  $h$ -th least significant digit of the binary representation of their index is null. In other words, a frequency  $f_i$  belongs to  $\Phi^h$  if the binary representation of  $i$  is  $b_{w-1}...b_0$ , where  $b_h = 0$ . Then the mapping  $\Gamma_h$  is introduced such that some input frequency  $f_i = f_0 + \Delta f \left( \sum_{l=0}^{w-1} 2^l b_l \right)$  in  $\Phi^h$  is mapped to  $\Gamma_h(f_i) = f_0 + \Delta f \left( \sum_{l=h+1}^{w-1} 2^l b_l + 2 \cdot \sum_{l=0}^h 2^l b_l \right)$  in  $\Phi^0$ , where  $b_{w-1}...b_0$  is the binary representation of  $i$ . The mapping  $\Gamma_h$  is an increasing up-conversion according to related U.S. Patent Application No. \_\_\_\_\_ (Attorney Docket No. 57983-000012, Client Reference No. 12867RO) referenced above.

The inverse mapping of  $\Gamma_h$  is also considered, which is denoted as  $\Gamma_h^{-1}$ . The mapping  $\Gamma_h^{-1}$  maps some input

frequency  $f_j = f_0 + \Delta f \left( \sum_{l=0}^{w-1} 2^l b_l \right)$  in  $\Phi^0$  to

$\Gamma_h^{-1}(f_j) = f_0 + \Delta f \left( \sum_{l=h+1}^{w-1} 2^l b_l + \frac{1}{2} \sum_{l=0}^h 2^l b_l \right)$  in  $\Phi^h$ , where  $b_{w-1} \dots b_0$  is the

5 binary representation of  $j$ . It is easy to see that the inverse mapping  $\Gamma_h^{-1}$  is an increasing down-conversion according to related U.S. Patent Application No.

(Attorney Docket No. 57983-000012, Client Reference No. 12867RO) referenced above.

10 Assuming that for some frequency  $f_i = f_0 + i\Delta f$  the binary representation of  $i$  is  $b_{w-1} \dots b_0$ . The shuffle  $\sigma_h$  is implemented with the increasing frequency up-conversion mapping  $\Gamma_h$  as follows:

- 1.) For any frequency  $f_i$  such that  $b_h = 0$ ,  $\sigma_h(f_i) = \Gamma_h(f_i)$ ; and  
15 2.) For any frequency  $f_i$  such that  $b_h = 1$ ,  
 $\sigma_h(f_i) = \Gamma_h(f_i - 2^h \Delta f) + \Delta f$ .

Similarly, the inverse shuffle  $\sigma_h^{-1}$  is implemented with the increasing frequency down-conversion mapping  $\Gamma_h^{-1}$  as follows:

- 20 1.) For any frequency  $f_i$  such that  $b_0 = 0$ ,  $\sigma_h^{-1}(f_i) = \Gamma_h^{-1}(f_i)$ ; and  
2.) For any frequency  $f_i$  such that  $b_0 = 1$ ,  
 $\sigma_h^{-1}(f_i) = \Gamma_h^{-1}(f_i - \Delta f) + 2^h \Delta f$ .

Therefore for some given value of  $h$  in the range  $0, \dots, w-1$ , shuffle and inverse-shuffle frequency permutations are  
25 efficiently implemented by a pair of frequency-shifters, a pair of identical constrained increasing logarithmic up-converters or down-converters, and wavelength-selective components. The function of the wavelength-

selective components is to selectively direct each frequency  $f_i$  to any of the frequency-shifters, or any of the logarithmic constrained increasing converters, according to the least significant digit (for the  
5 corresponding inverse shuffle permutation), or according to the  $h+1$ -th least significant digit (for the corresponding shuffle permutation) of the binary representation of the frequency index  $i$ .

The above equations naturally lead to the designs of  
10 that are shown in Figure 18 and 19. In Figure 18, frequency shuffler 1800 takes distinct frequencies at the input. These incoming frequencies are directed to two types of outputs by a first wavelength router 1801. A first type of output from wavelength router 1801 receives  
15 any input frequency  $f_i$  such that  $b_h=1$ . This first set of frequencies are then shifted by  $-2^h\Delta f$ , by frequency shifter 1803 and then sent to an increasing up-converter 1807 that implements the mapping  $\Gamma_h$ . The frequencies that leave increasing up-converter 1807 are shifted by an  
20 amount  $\Delta f$  by frequency shifter 1806 and then sent as inputs 1805 to a second wavelength router 1804. Wavelength router 1801 produces a second type of output 1808 that receives any input frequency  $f_i$  such that  $b_h=0$ . Frequencies of this second set are sent to a second  
25 increasing up-converter 1809 that also implements the mapping  $\Gamma_h$ . The frequencies that leave increasing up-converter 1809 are sent as inputs 1810 to the wavelength router 1804.

In Figure 19, the inverse frequency shuffler 1900  
30 takes distinct frequencies at the input. These incoming frequencies are directed to two types of outputs by a

first wavelength router 1901. A first type of output from wavelength router 1901 receives any frequency  $f_i$  such that  $b_0=1$ . This first set of frequencies are then shifted by  $-\Delta f$  by frequency shifter 1903 and then sent to an increasing down-converter 1907 that implements the mapping  $\Gamma_h^{-1}$ . The frequencies that leave down-converter 1907 are shifted by an amount  $+2^h \Delta f$  by frequency shifter 1906 and then sent as inputs 1905 to a second wavelength router 1904. Wavelength router 1901 produces a second type of output 1908 that receives any input frequency  $f_i$  such that  $b_0=0$ . Frequencies of this second set are sent to a second increasing down-converter 1909 that also implements the mapping  $\Gamma_h^{-1}$ . The frequencies that leave down-converter 1909 are sent as inputs 1910 to wavelength router 1904.

##### 5. Overall Converter Complexity

The converter costs of the different components of the SW-Banyan architectures described above are summarized in the table of Figure 26. The total number of frequency shifters is  $2 \log_2(W) - 1$ . When frequency shifters are built as cascaded wavelength converters based on difference-frequency generation, the cost doubles to  $4 \log_2(W) - 2$ . Therefore, the converter complexity is  $O(\log_2 W)$  instead of  $O(W)$ . It is straightforward to perform similar computations for other self-routing networks. The results are summarized in the table of Figure 27. This small complexity subsequently enables the building of multi-log networks that are based on the SW-Banyan network, are rearrangeably or strictly non-blocking and still have a low converter complexity of  $O((\log_2 W)^n)$ , where  $n$  is some

small integer constant .

#### 6. Example

In Figures 20 to 23 there is shown an application of  
5 the techniques described in previous sections to the 8x8  
self-routing SW-Banyan network of Figure 9. The overall  
design uses ten frequency shifters.

#### D. Multi-Log Wavelength Interchangers

10

##### 1. Design

As described above, there are economical ways to  
implement self-routing wavelength interchangers. In  
wavelength switching networks, the self-routing property  
15 does not provide any benefits, but rather leads to  
blocking. In self-routing networks blocking occurs  
because there is a unique path for each input-output  
pair, and some switching elements are shared by more than  
2 input-output pairs (see A. Pattavina referenced above).  
20 To remove this problem, well-known techniques are  
horizontal extensions and vertical replications as  
described above. These techniques allow rearrangeable or  
strictly non-blocking multi-log networks to be built  
starting from self-routing networks. These techniques can  
25 also be applied to self-routing wavelength interchangers  
built in accordance with the present invention.

In the case of the SW-Banyan network, a  $\log_2(W, m, p)$   
wavelength interchanger can be provided based on the SW-  
Banyan wavelength interchangers described above, as shown  
30 in Figure 24. That is, Figure 24 shows a  $\log_2(W, m, p)$   
wavelength interchanger wherein each incoming frequency  
is directed to one of the  $p$  stacked copies of a

Many variations of this basic architecture may be obtained according to the choice of specific technologies to build multiplexers, switching elements, inter-stage connection modules, and other components that are implied by the architecture. However, these issues have also been addressed above. Also, it is straightforward to provide a similar description for multi-log networks built out of

other self-routing networks such as the n-cube, omega, or baseline networks. The only change to be done is to replace the inter-stage connection modules appropriately. As previously mentioned, the blocking characteristics of multi-log networks depend on the quantitative relationships between the parameters of the network. Thus, it is now appropriate to focus on multi-log networks built out of SW-Banyan self-routing networks and evaluate the converter complexity of the architecture for specific values of the parameters that correspond to rearrangeably or to strictly non-blocking networks.

## 2. Converter Complexity

For some arbitrary  $\log_2(W, m, p)$  network built according to the design of Figure 24, the frequency shifter complexity is  $p[2\log_2(W) + 2m - 2]$ . According to previous work on multi-log networks, the wavelength interchanger becomes rearrangeable if any of the following conditions is satisfied:

- 1.)  $p \geq 2^{\frac{w-m}{2}}$ , where  $w = \log_2 W$
- 2.)  $p = 1$ , and  $m = w - 1$

A near-optimal alternative to obtain a rearrangeably non-blocking  $\log_2(W, m, p)$  wavelength interchanger with a reduced frequency shifter complexity is to meet the second condition. In this case, the overall frequency shifter complexity of the rearrangeably non-blocking wavelength interchanger is  $4\log_2(W) - 4$ . When these interchangers are used in separable cross-connects according to the design of Figure 8 above, rearrangeably non-blocking  $(FW) \times (FW)$  wavelength-interchanging cross-connects are obtained with a total frequency shifter complexity of  $O(F \cdot \log_2 W)$ .

To obtain a strictly non-blocking multi-log wavelength interchanger,  $p$  needs to be selected according to the following criteria:

$$p \geq \begin{cases} \frac{3}{2} \cdot 2^{\frac{w-m}{2}} + m - 1, & w+m \text{ even} \\ \frac{w-m+1}{2} + m - 1, & w+m \text{ odd} \end{cases}, \text{ where } w = \log_2 W.$$

- 5 A near optimal frequency shifter complexity is obtained with  $\log_2(W, \log_2(W)-1, \log_2(W))$ , where the frequency shifter complexity is  $4 \cdot \log_2(W)(\log_2(W)-1)$ . All of the above-mentioned results are summarized in the table of Figure 28, wherein  $w = \log_2 W$  and  $F$  is the number of fibers.
- 10 In summary, the present invention provides a novel approach to building wavelength-interchanging cross-connects (i.e., all-optical cross-connects capable of changing the frequency of incoming signals). The new approach is characterized by a new wavelength-to-space
- 15 transformation and new ways to exploit wave-mixing converters. The main principle of the transformation is to assign frequency  $f_{i \bmod W}$  to some inlet or outlet  $i$  in each stage, where  $W$  is the number of frequencies in the system. Through this transformation, well-known space-
- 20 switch architectures can be naturally extended to the wavelength domain. Wave-mixing converters are also used to provide cost-effective implementations of the new cross-connects. In the architecture, wave-mixing converters serve to change the states of the switching
- 25 elements and to provide inter-stage connections. Overall, the new approach enables the construction of wavelength-interchanging cross-connects with significantly reduced converter requirements. Indeed, some examples of wavelength-interchanging cross-connects are shown with a
- 30 converter complexity of  $O(F(\log_2 W)^n)$ , where  $F$  is the number



of fibers, and  $n=1,2,3$ . This compares favorably with previous designs that have converter complexities of  $O(FW)$ .

5 The present invention is not to be limited in scope by the specific embodiments described herein. Indeed, various modifications of the present invention, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such  
10 modifications are intended to fall within the scope of the following appended claims. Further, although the present invention has been described herein in the context of a particular implementation in a particular environment for a particular purpose, those of ordinary  
15 skill in the art will recognize that its usefulness is not limited thereto and that the present invention can be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full  
20 breath and spirit of the present invention as disclosed herein.